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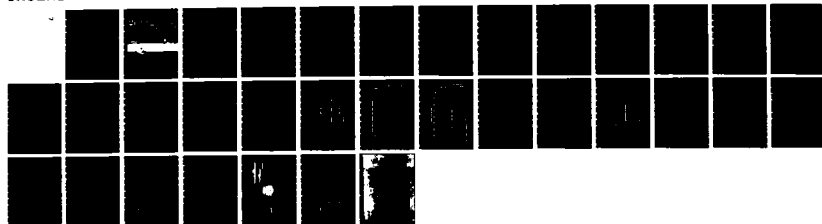
DETERMINING THE TOTAL SHIP RELIABILITY DISTRIBUTION(U)  
ASSOCIATION OF SCIENTISTS AND ENGINEERS OF THE NAVAL  
SEA SYSTEMS COMMAND WASHINGTON DC P HARTMAN ET AL  
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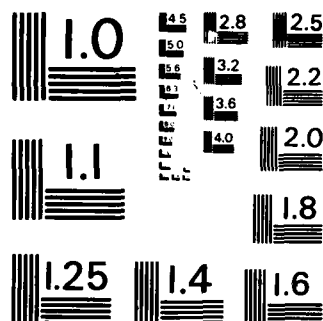
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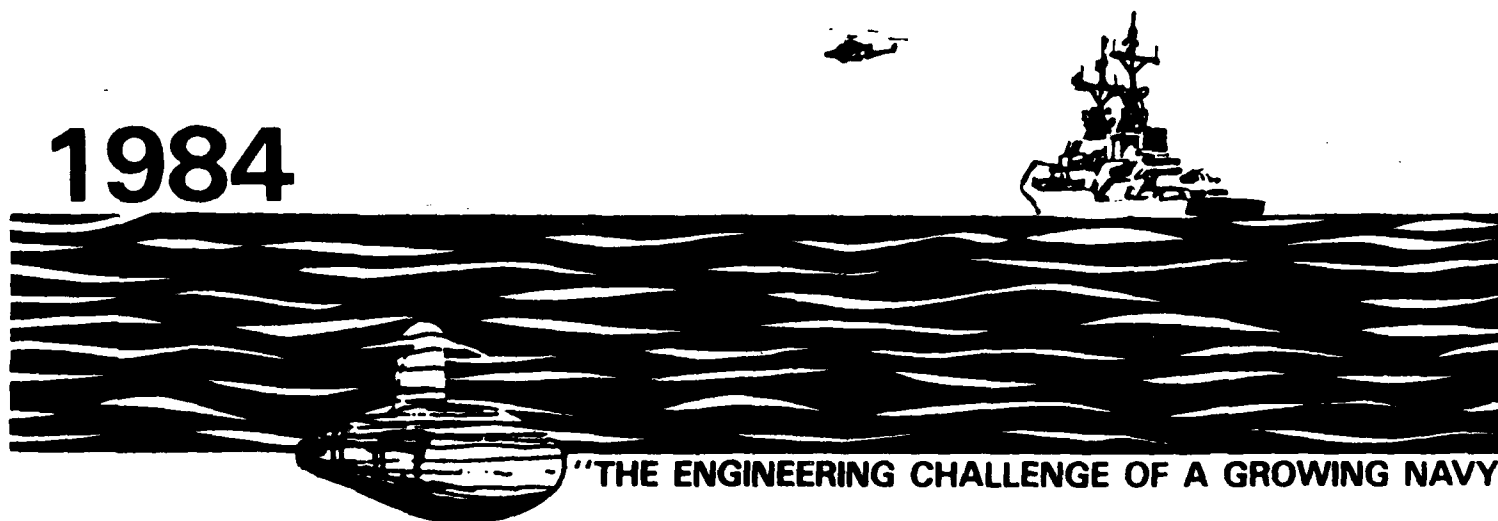
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1984



"THE ENGINEERING CHALLENGE OF A GROWING NAVY"

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DETERMINING THE TOTAL SHIP RELIABILITY DISTRIBUTION

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Palmer Luetjen  
Morton Buckberg*



**Determining The Total Ship Reliability Distribution**

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**Materials and Assurance Engineering Office  
Naval Sea Systems Command**

**March 1984**

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# ABSTRACT

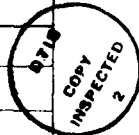
(1/1000 time between failures)

Acquisition cost and reliable equipment performance are two primary considerations in procurement decisions for ships and ship systems. An important question in this decision process is, how does the variation in equipment failure rate (performance quality) effect the satisfactory operation of the total system. Until recently the effect of equipment performance quality has been difficult to predict.

A new method of analysis has been developed which models variation in equipment failure rate (1/MTBF) with the gamma distribution, calculates the system's response to this MTBF variation, and replicates the performance of the parent distribution with the cumulative beta distribution. Once determined, the cumulative beta distribution enables the engineer or naval architect to easily calculate the upper and lower limits of performance for the parent reliability distribution.

The distribution of MTBFs for 115 "identical" commercial computers is shown as an illustration of equipment performance quality variation discussed. Example cases using the gamma and beta distributions are shown to demonstrate ease of use.

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## I. Introduction

Increasingly sophisticated computer simulations have been developed by NAVSEA OSMR to predict the reliability, maintainability, and availability (RMA) of total ships based on the failure and repair characteristics of the hundreds of essential equipment which make up the ship.

The most sophisticated of these simulations, TIGER, (References 1,2) has been used to analyze each Navy ship class constructed during the past decade as exemplified in Figures 1 and 2. This computer program can be used to analyze the sensitivity of total ships and systems to variations in equipment performance quality. The distribution of mean time between failures (MTBFs) of 115 "identical" commercial computers (Reference 3) is shown as an illustration of the "quality" variation discussed.

## II. Reliability Impact of Spares Quality

Consider the complexity associated with supplying Navy combatant ships with spare parts for hull mechanical and electrical (HM&E) machinery. For example, failure of the main propulsion system would seriously degrade a ship's ability to perform a primary warfare mission. Spares are carried at sea for routine maintenance. The supply system allocates spares for each maintenance level. The three levels of maintenance are:

- o organizational (ships crews)
- o intermediate (tender or Navy specialized activity)
- o depot (Navy or commercial shipyard or industrial activity)

In this paper we will concentrate on parts support for the organizational level of maintenance.

HM&E equipment is designed integral to the ships hull and is intended to have a life equal to the service life of the ship. It is not cyclic; it does not become obsolete every ten years, but it does require substantial maintenance and overhaul and in many cases survives longer than its original manufacturer.

Essentially, preventive maintenance tasks consist of cleaning, purification, lubrication, packing and sealing, and condition monitoring. Navy ships because of their global commitments may take on a variety of contaminated substances. The most critical to the ship's performance and equipment life is main propulsion fuel oil where the contaminants include sulphur, dissolved metals, sludge, seawater, etc. If the preventive maintenance tasks are not completed properly on a rigorous schedule, failures are induced prematurely and wear-out begins. Overhaul or replacement is required taking the combatant out-of-service. What happens then to a fifteen year old main propulsion diesel engine, overhauled twice, showing an increased failure rate, and a decreased time between overhauls. Where do the spare parts come from? Who makes them? How reliable are the repair parts/components, etc.

If the Navy owns the manufacturing drawings, competitive procurement is required by law and the lowest bidder "qualified" receives the award. Does the drawing contain sufficient information to enable replication of the original part? Most often the answer is no. Proprietary manufacturing processes, tolerances and material-treating vary considerably among suppliers. The resulting parts are look-alikes, but will their MTBFs live up to the original parts. For example, an attached lube oil pump manufactured by other than the original equipment suppliers does not have a preproduction unit tested by mounting on the engine and subjected to the environmental stresses of the original pump. How long it will last is not determined until placed in service. There is not sufficient incentive for the manufacturer to produce more reliable, better quality part and the Navy does not normally test part reliability and quality prior to Fleet use. The results can be catastrophic to ship availability and performance - an unacceptable operational limitation. We must be able to predict parts criticality; predetermine the cost penalties for poor reliability and quality, and standardize high reliability and quality into the parts procurement process. Figure 3 shows the drastically increased maintenance burden incurred when the MTBF of replacement parts does not meet the value to which the system was designed.

### III. Distribution of Spares MTBFs

There is considerable scatter in the failure data used to obtain the "point estimate" of MTBF. Each unit is unique and construction or use can produce variation in the distribution of MTBFs. Good quality control in manufacturing and rigorous operating philosophies can reduce the variance and result in a



sharply peaked probability density function (pdf) with a sample population concentrated around the mean of the distribution. More scattered MTBF distributions have been observed in actual practice. Reference 3 presented a histogram of MTBF's of 115 "identical" computers in which the range of MTBF's extended from 200 to 7200 hours, mean 1740 hours, standard deviation 1450 hours. This histogram data has been reduced and fit with the gamma distribution which is defined for MTBFs ranging from zero to infinity. (References 4, 5, & 6, see Appendix A). The cumulative distribution function (CDF) of this data is plotted in Figure 4. Figure 5 depicts a case in which there is considerable scatter in the MTBF values, with the majority of the MTBFs falling below 2000 hours and a few beyond 4000 hours. In a distribution, like this, skewed to the right, (Figure 5) the median and mode both occur at values less than the distribution mean.

The mean and unbiased standard deviation of the histogram data were used to determine whether or not the two parameter, integer gamma distribution fits the observed MTBF distribution. Figure 4 shows that the gamma distribution with an integer shape factor of  $b=2.0$  fits the general distribution of the data quite well. (See Appendix A and Reference 7 for analysis used.)

If there is very little deviation in MTBF and the distribution approximates a spike, the point estimate yields a very good prediction of operation in the field, but the variation shown in Figure 4 significantly effects the reliability of the system. As pointed out previously, an MTBF distribution skewed to the right (gamma) has significantly more than half of its MTBF values below the mean. Therefore system reliability predictions from the point estimate will be higher than actually observed in the field more than half the time.

#### IV. Modeling System Sensitivity with the Cumulative Beta Distribution

Overall, the gamma distribution closely represents "real world" variation in these MTBF values and allows direct use in conjunction with existing total ship reliability simulations through the use of a compact subroutine developed in References 8 and 9 for high speed computer generation of gamma distributed variates. The inputs for this subroutine are the mean and standard deviation of the underlying distribution.

Test cases have been prepared to illustrate the methodology required to determine total system sensitivity to variation in equipment MTBF. System 1 of Figure 6 consists of two different types of equipment (X and Y) each of which exhibit exponentially (References 10 & 11) distributed failure probabilities with MTBFs of 150 and 200 hours respectively.

Example cases are calculated using two reliability block

diagrams (RBDs) of Figure 6 for equipment X and Y; a simple series system (System 1) and a series system in which each block has a standby to be operated upon failure of the first (System 2).

Table 1 shows significant variation in reliability at 25 and 100 hours (mission time) for this system when its MTBFs follow a gamma distribution as might happen when spares are procured at different times from various manufacturers (Figure 7). By Equation 1, of Appendix A, equipment X has a point estimate reliability of 0.85 at 25 hours and equipment Y yields 0.88. The reliability of System 1 is the product of these two reliabilities or 0.75, but not many of the units have met the reliability predicted from the point estimate.

For the 100 hour example, less than 50% of the samples have a reliability of 0.2 or better. Table 1 illustrates the distribution of 25 and 100 hour reliabilities obtained with the gamma distributed MTBFs presented earlier. To determine the distribution of System 1 reliabilities, the data was analyzed and fit with the beta distribution which is ideally defined for the zero to one range of the reliability parameter. (References 4, 5, & 6, see appendix A).

By calculating the mean and unbiased estimates for the standard deviation and variance of the reliability data, the two parameters of the beta distribution can be obtained. (Reference 12). Figure 8 shows the probability density functions obtained for the time data in Table 1 using the beta distribution. Figure 9 shows the cumulative beta distribution (incomplete beta function) for 25 and 100 hour System 1 reliability data. The distribution (solid line) passes through the actual data points taken from Table 1, median ranked as in Reference 13 to determine each point's representative portion of the total population CDF.

The cumulative beta distribution accurately estimates the system's reliability distribution and provides for calculation of the percentile of this reliability distribution. As shown in Figure 9, 90% of the population (10th percentile) has a reliability of 0.50 or greater after running 25 hours.

These examples indicate that the cumulative beta distribution estimates the percentiles for a system reliability distribution. The procedure for determining the reliability distribution is straight-forward and computationally efficient. Only ten predictions of system reliability were required for the test case shown.

Figure 10 shows the enhanced reliability increase performance of the System and quantifies the increased reliability gained by installing a standby unit as a back up. The reliability increase obtained by adding a standby unit is evident from the shift in 25 and 100 hour reliabilities to higher levels than those achieved

with the simple series system in Figure 9. Note that the cumulative beta distribution is capable of fitting the reliability performance distributions of high and low reliability systems. This is a feature of the right and left hand symmetry (coefficients A and B in Equation 4 References 5 and 10; see Appendix A) that exists with the beta distribution.

#### V. Calculating The Reliability Distributions For Very Large Systems

Simple hand calculations are not sufficient to predict the reliability of these complex systems References 14 and 15. Simulations such as NAVSEA'S TIGER computer program (Reference 1) calculate the failure and repair characteristics of systems containing several hundred to several thousand different types of equipment (see Figures 2 & 13). Note that in these systems, complex operating rules are required to efficiently perform the analysis of the time dependent reliability. The range of TIGER analyses covers the transistor level, ship level, and multi-ship task force R&M assessments.

#### VI. Conclusions

The quality of ship board spares and their MTBF variation does make a difference in the distribution of total system reliability performance. Significantly different MTBFs can be obtained with "look-alikes" from different vendors. This investigation showed that the real world data is skewed and that the MTBFs of some highly complex equipment were gamma distributed. Reliability calculations based on the mean of the MTBF distribution can be significantly higher than those determined with an MTBF distribution skewed to the right as with the gamma. This points out a problem; since spares may not live up to the MTBFs of the original equipment, the in service reliability may be significantly lower than predicted unless the variance of the MTBFs is symmetrically distributed.

The NAVSEA TIGER R&M computer program used with gamma distributed MTBFs and the cumulative beta distribution enables the engineer and architect to rapidly determine the upper and lower limits of total system reliability performance.

Very few calculations were required for the example cases shown here. The only data required to calculate the beta distribution parameters were the mean and unbiased estimate of the standard deviation of the system's reliability values as obtained from the standard NAVSEA TIGER R&M computer runs. The two parameter cumulative beta distribution fits the reliability data well and provides an easy method of calculating the percentiles of the parent distribution for various forms of distributed equipment data.

## VII. References

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## Appendix A

### Reliability and the Gamma and Beta Distribution Functions

# NOMENCLATURE:

a	gamma distribution, scale factor
b	gamma distribution, shape parameter
A	beta distribution, first parameter
B	beta distribution, second parameter
C	mean of the beta distribution
D	variance of the beta distribution
e	2.7182... base of natural system of logarithms
f(t)	probability density function (pdf) of the failure distribution at time t
F(t)	cumulative distribution function(CDF) of the f(t) being examined, the probability that an equipment has failed at or before time t
$\Gamma( )$	gamma function
$\lambda(t)$	instantaneous failure rate for exponential systems
m	arithmetic mean of the data set
MTBF	Mean Time Between Failures
MTTF	Mean Time to (First) Failure
N	number of failures or number of units failed
pdf	probability density function
R	reliability = $1 - \text{Pr}(\text{fail}) = 1 - \int_0^t f(t) dt = 1 - F(t)$
$\hat{s}$	unbiased standard deviation of the data using N-1 sample factor
t	time in hours

## RELIABILITY CHARACTERISTICS:

For the exponential case, the reliability of any single equipment is (References 10 & 11)\*:

$$R = e^{(-\lambda t)} \quad (1)$$

How long an individual equipment performs depends on its mean time between failures (MTBF) for repairable units and means time to failure (MTTF) for nonrepairable cases (1). MTBF is defined as:

$$MTBF = \Sigma t / \text{number of failures} \quad (2)$$

The MTBF calculation is often history dependent and exhibits an increasing hazard rate since the success paths in most simple systems having redundancy decrease with time (10). In the case of the exponential equipment, the hazard rate is constant and thus MTBF equals MTTF where:

$$MTTF = \Sigma t / \text{number of units tested} \quad (3)$$

System performance can be enhanced by increasing the MTBF or MTTF of the individual units through better design, less severe operating environments, and by adding standby units to take over upon failure. Figure A-1 shows that standby redundancy is effective, but at substantial cost; e.g., another unit, installation cost, supporting structure, and maintenance burden.

$$R = e^{(-\lambda t)} + \lambda t e^{(-\lambda t)} \quad (4)$$

The added reliability obtained by adding a standby unit is evident in Equation (4).

\* References for appendix are the same as shown in the body of the paper.



### GAMMA DISTRIBUTED MTBFs:

The "real world" differs from Equation (2) in that there is considerable scatter in the life data used to obtain the "point estimate" of MTBF. This fact was graphically presented in a histogram of MTBFs for 115 "identical" computers in Reference 3. The data from this histogram has been extracted and presented in Table A-1.

The case in which there is considerable scatter in the MTBF values, with the majority of the failures taking place quite early and a few units lasting much longer. In a distribution skewed this way (right), the median and mode both occur at values less than the distribution point estimate (the mean, Equation (2)).

This type of MTBF distribution has been observed in actual practice. The mean and unbiased standard deviation of the data are used to determine the two parameter, integer gamma distribution fit to the observed MTBF distribution. The gamma distribution (References 4, 5, and 6) equals:

$$f(t;a,b) = \frac{a^b t^{(b-1)} e^{(-at)}}{\Gamma(b)} \quad (5)$$

where;       $0 \leq t < \infty$   
               $a \geq 0$  and  
               $b \geq 0$ .

Some of the deviation from the actual data can be accounted for by the use of an integer shape factor  $b=2.0$  versus the 1.4 calculated from the mean and standard deviation of the data set. Additional divergence appears to be caused by the complex (bimodal) distribution of the data set itself which is evident as two distinct, straight lines when plotted on Weibull paper as shown in Reference 7.

The bimodal attributes of the computer MTBF data is characterized by two distinct straight lines. Note that the right hand curve (1000 to 10000 hour MTBF) has a Weibull shape slightly greater than 1.0 indicating an exponential distribution whereas the left curve is definitely non-exponential with a shape of 2.0. (Figure A-2)

## BETA DISTRIBUTION

Reliability values obtained from the parent distribution are fit with the beta distribution (References 4, 5, 6); where the beta distribution is defined as:

$$f(y:A,B) = \frac{\Gamma(A+B)}{\Gamma(A) \Gamma(B)} (y)^{(A-1)} (1-y)^{(B-1)} \quad (6)$$

where;

y is the variable of interest and  $\Gamma(A)$  is the gamma function with A as its argument.

To provide a replicate of the parent. The mean of the beta distribution is:

$$C = \frac{A}{A+B} = m \quad (7)$$

and the variance is:

$$D = \frac{AB}{[(A+B)^2 (A+B+1)]} = s^2 \quad (8)$$

Solving these Equations (7 and 8) for the two unknowns (A and B) as a reference (12):

$$A = \frac{(C^2 - C^3 - CD)}{D} \quad (9)$$

and

$$B = \frac{(C - 2C^2 + C^3 + CD - D)}{D} \quad (10)$$

By calculating the mean and unbiased estimates for the standard

deviation and variance of the reliability data, the parameters A and B of the beta distribution can be obtained.

The cumulative beta distribution accurately quantifies the system's reliability distribution and provides for the calculation of the lower confidence limits of system performance.

The cumulative beta distribution is:

$$F(R;A,B) = \int_0^R f(y;A,B)dy \quad (11)$$

where:

$$0 \leq R \leq 1, \\ A \geq 0, \text{ and } B \geq 0.$$

The replicate distribution of the parent distribution is a specimen of the parent. The replicate distribution will have Q number of samples with each sample consisting of one observation (sample size N=1). For a continuous parent distribution sampling may be with or without replacement. The replicate asymptotically approaches the parent as the number of samples ,Q, increases.

The beta fit method, for prediction, is used in lieu of the coverage calculations, for demonstration, using order statistics Ref. 4. The beta percentile is used as the estimator for the fractile of the parent distribution.

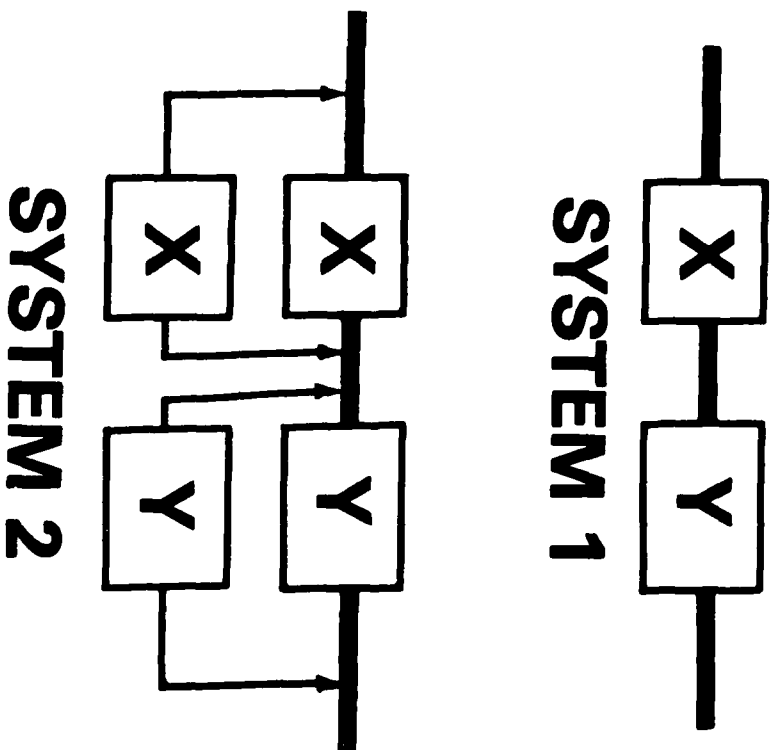
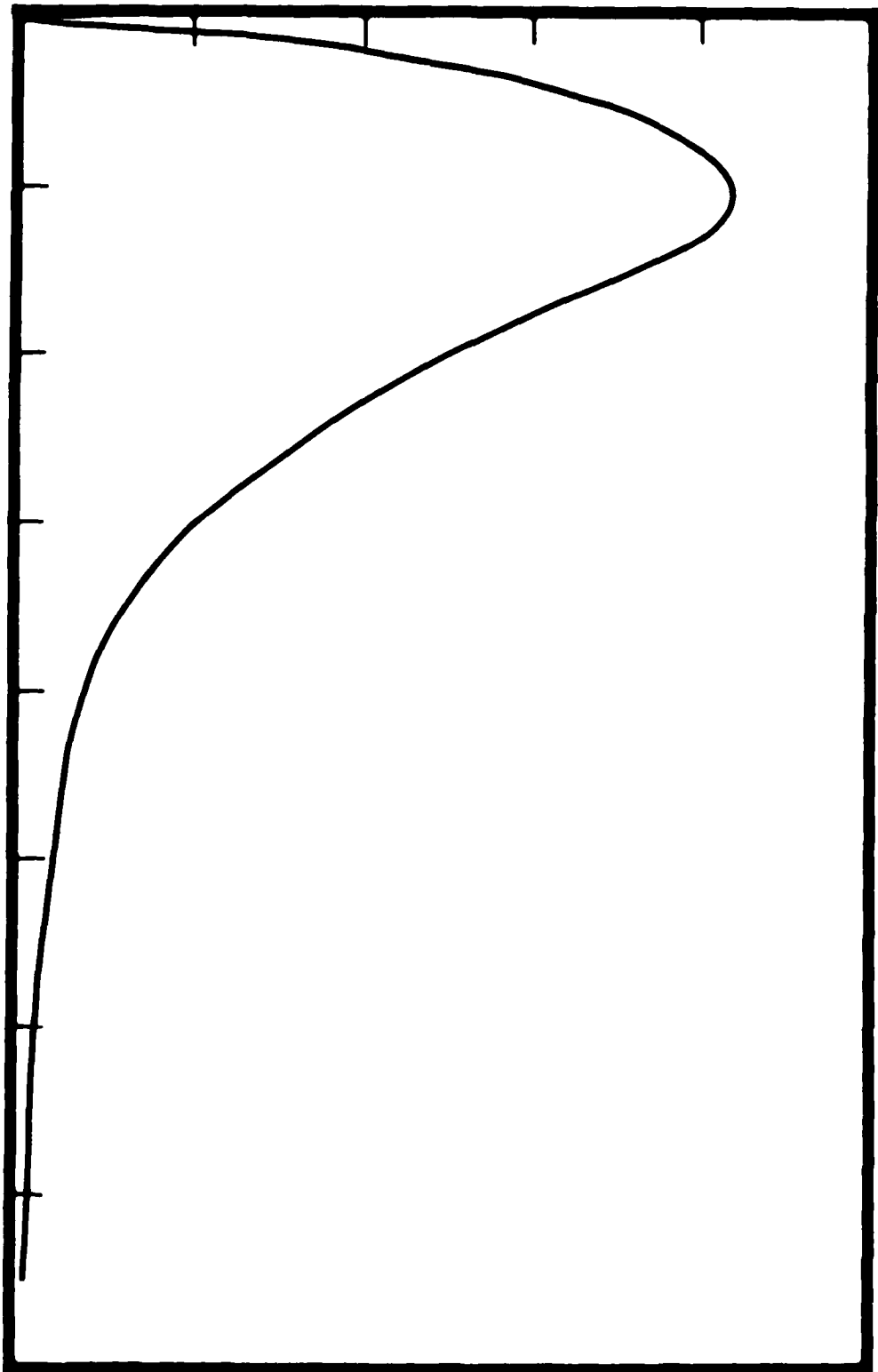


Figure 6. Series and Standby Reliability Block Diagrams (RBDs)

**RELATIVE FREQUENCY OF OCCURRENCE**



**EQUIPMENT MEAN TIME BETWEEN FAILURES (MTBF)**

Figure 5. Typical Shape of the Gamma Probability  
Distribution Function (pdf)

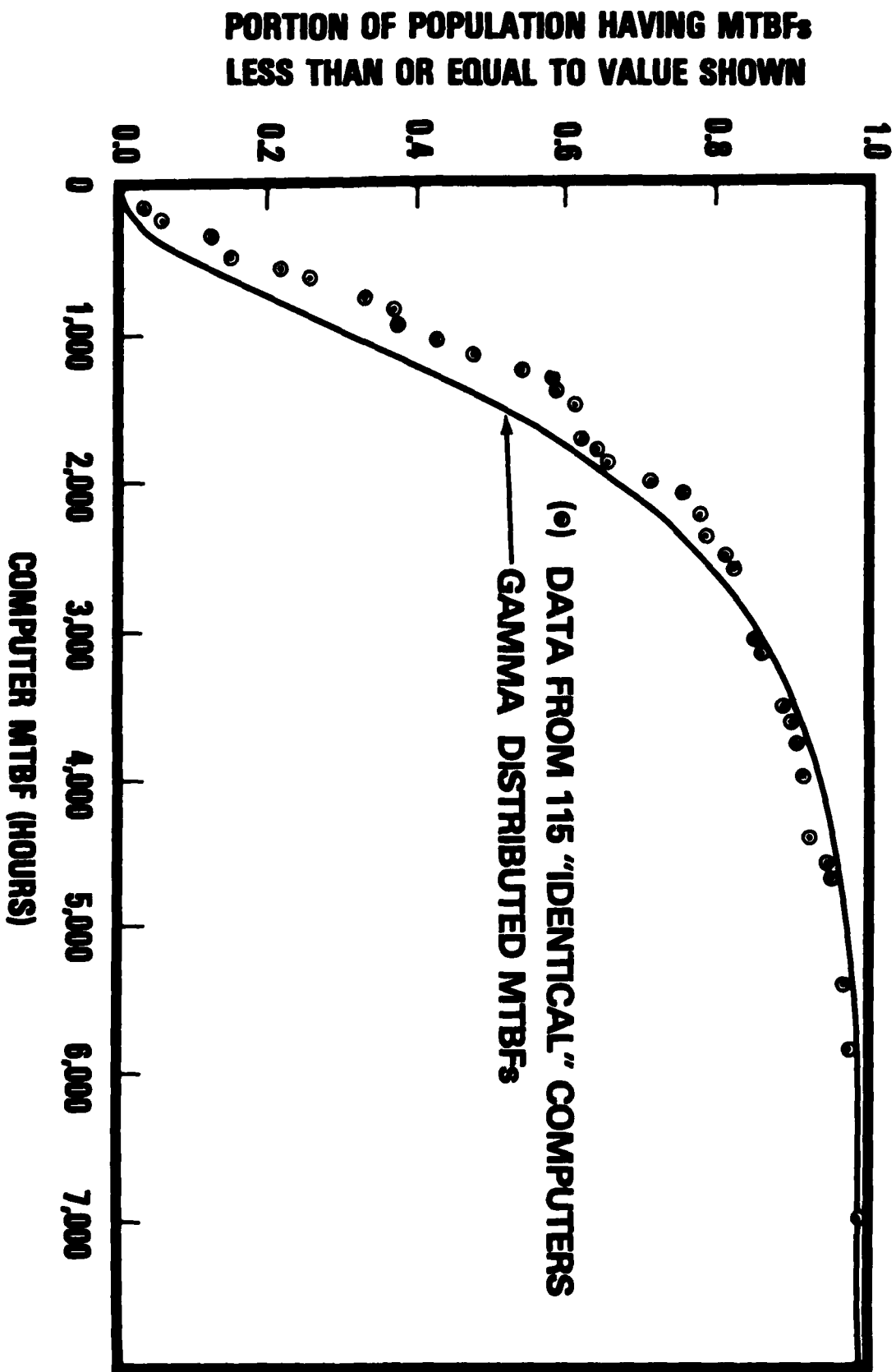


Figure 4. MTBF Data for Commercial Computers Fit  
with the Gamma Cumulative Distribution Function

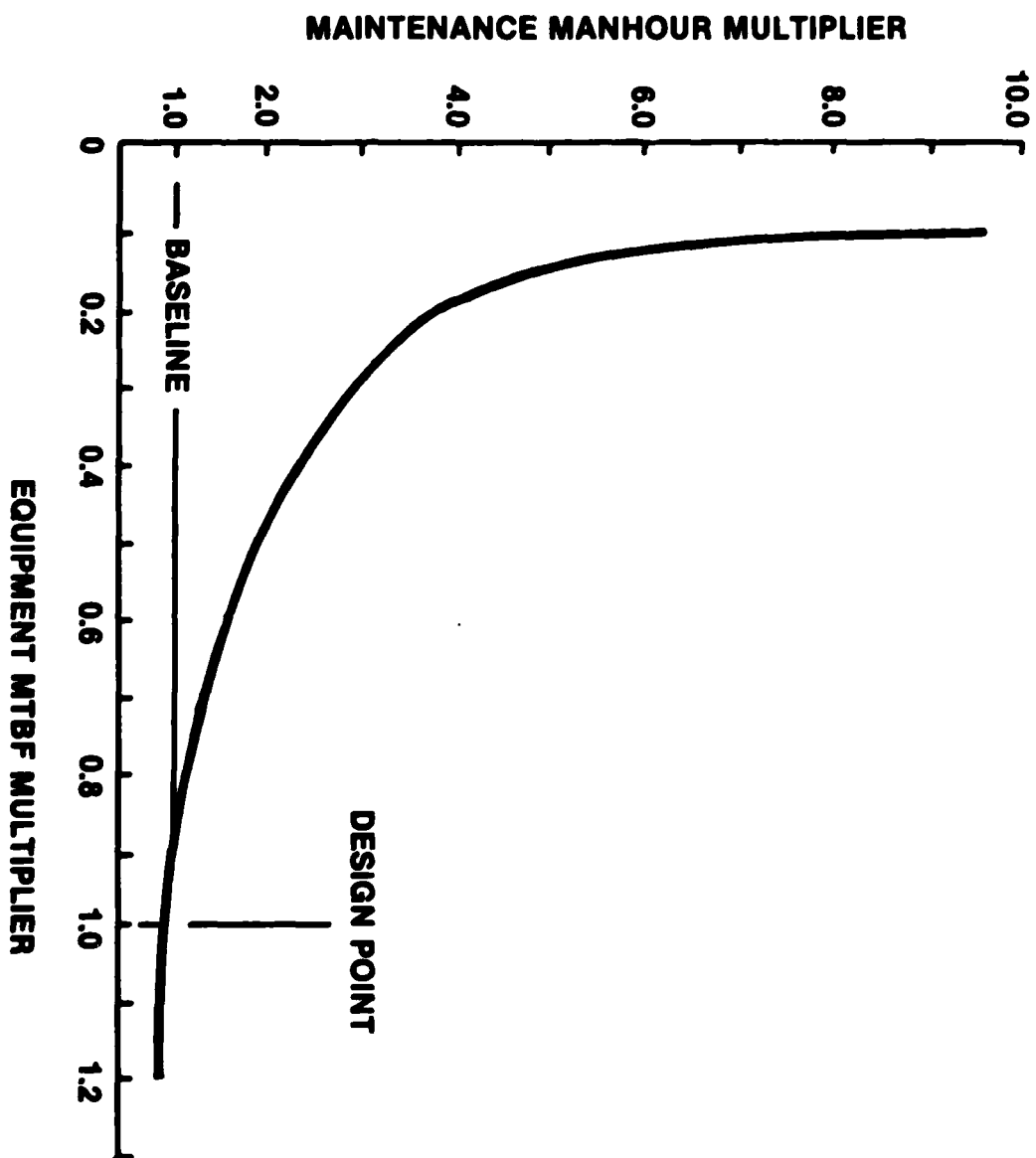


Figure 3. The Increased Maintenance Burden  
Caused by Lowered Equipment MTBFs

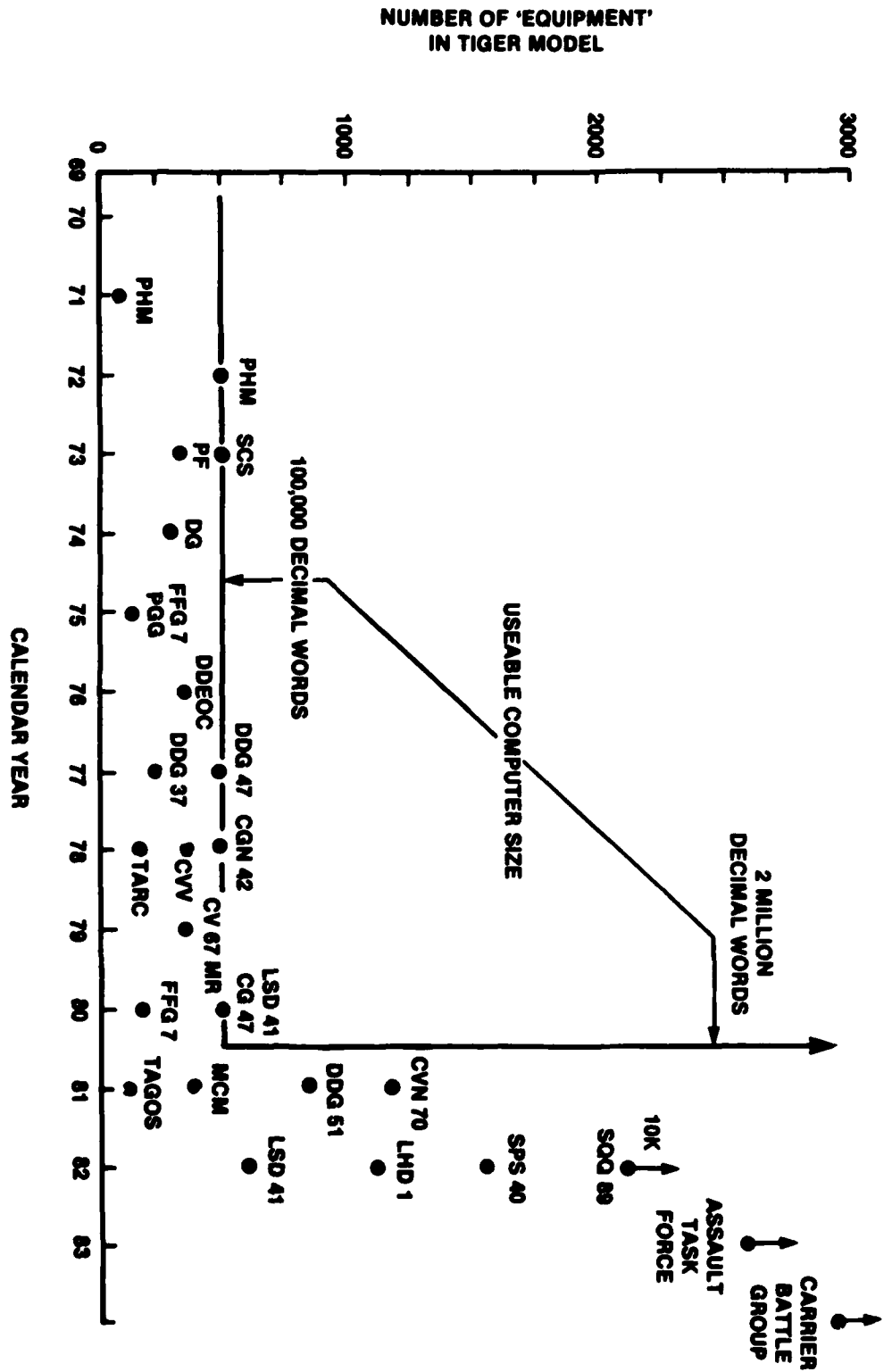


Figure 2. NAVSEA TIGER R&M Analyses



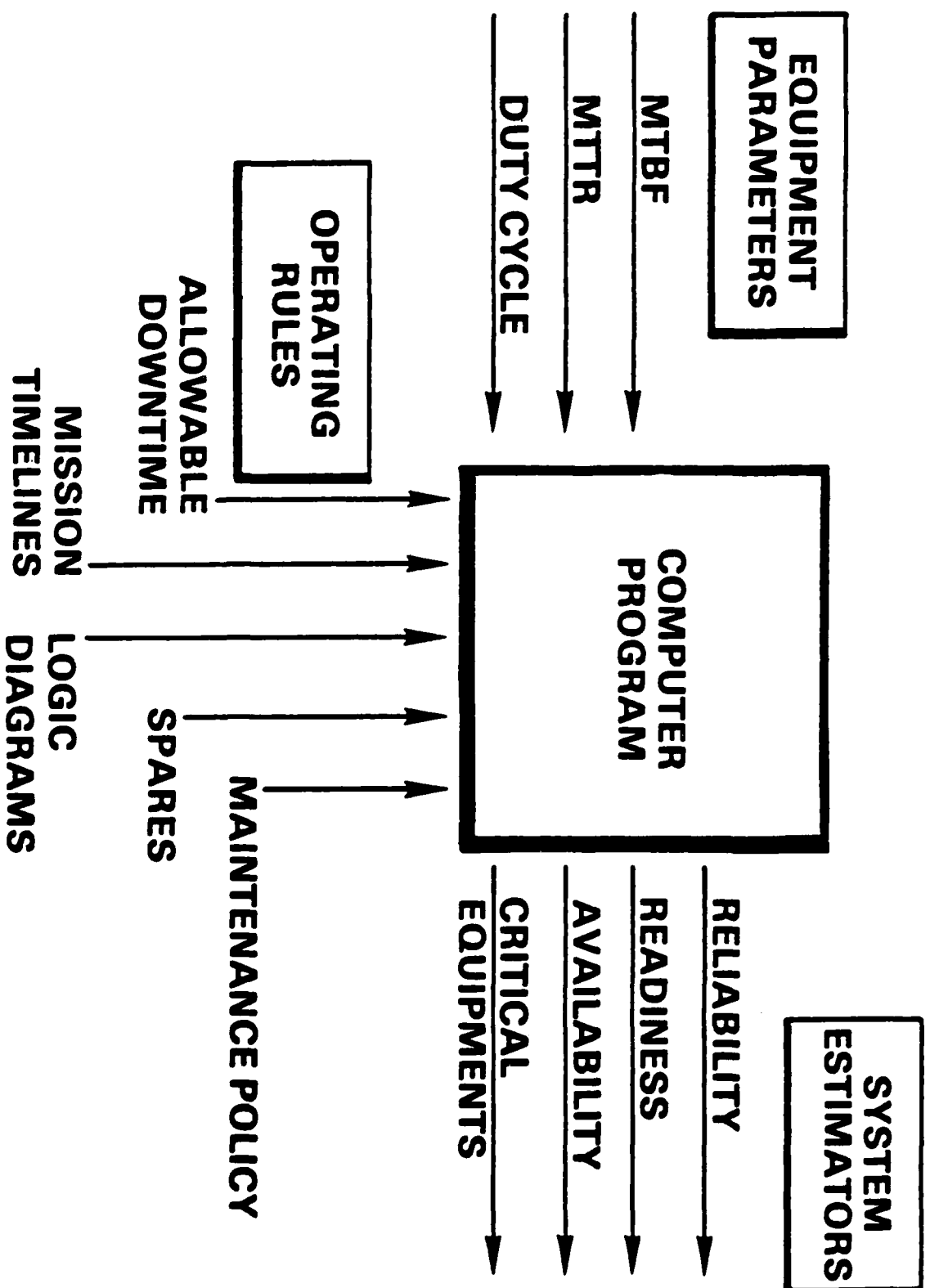


Figure 1. TIGER Computer Program Flow

Table A-1 MTBF Samples From 115 "Identical" Computers  
For One Year's Operation

MTBF Class Mark** (Hours)	Frequency of occurrence ( $f_i$ )	Cumulative Distribution Function $\frac{\sum f_i}{n}$
50	0	0.0
150	2	0.02
250	3	0.04
350	7	0.10
450	5	0.15
550	7	0.21
650	5	0.25
750	9	0.33
850	2	0.35
950	2	0.37
1050	6	0.42
1150	5	0.46
1250	8	0.53
1350	4	0.57
1450	2	0.58
1550	3	0.61
1750	1	0.62
1850	5	0.66
1950	1	0.67
2050	4	0.70
2150	6	0.76
2250	2	0.77
2450	1	0.78
2550	3	0.81
2650	1	0.82
3150	5	0.86
3350	1	0.87
3550	1	0.88
3650	1	0.89
3750	1	0.90
4050	2	0.91
4450	2	0.93
4550	3	0.96
4650	1	0.97
5450	1	0.97
5850	1	0.98
7050	1	0.99
7150	1	1.0

\*\* 100 Hour Class Interval Reference 3.

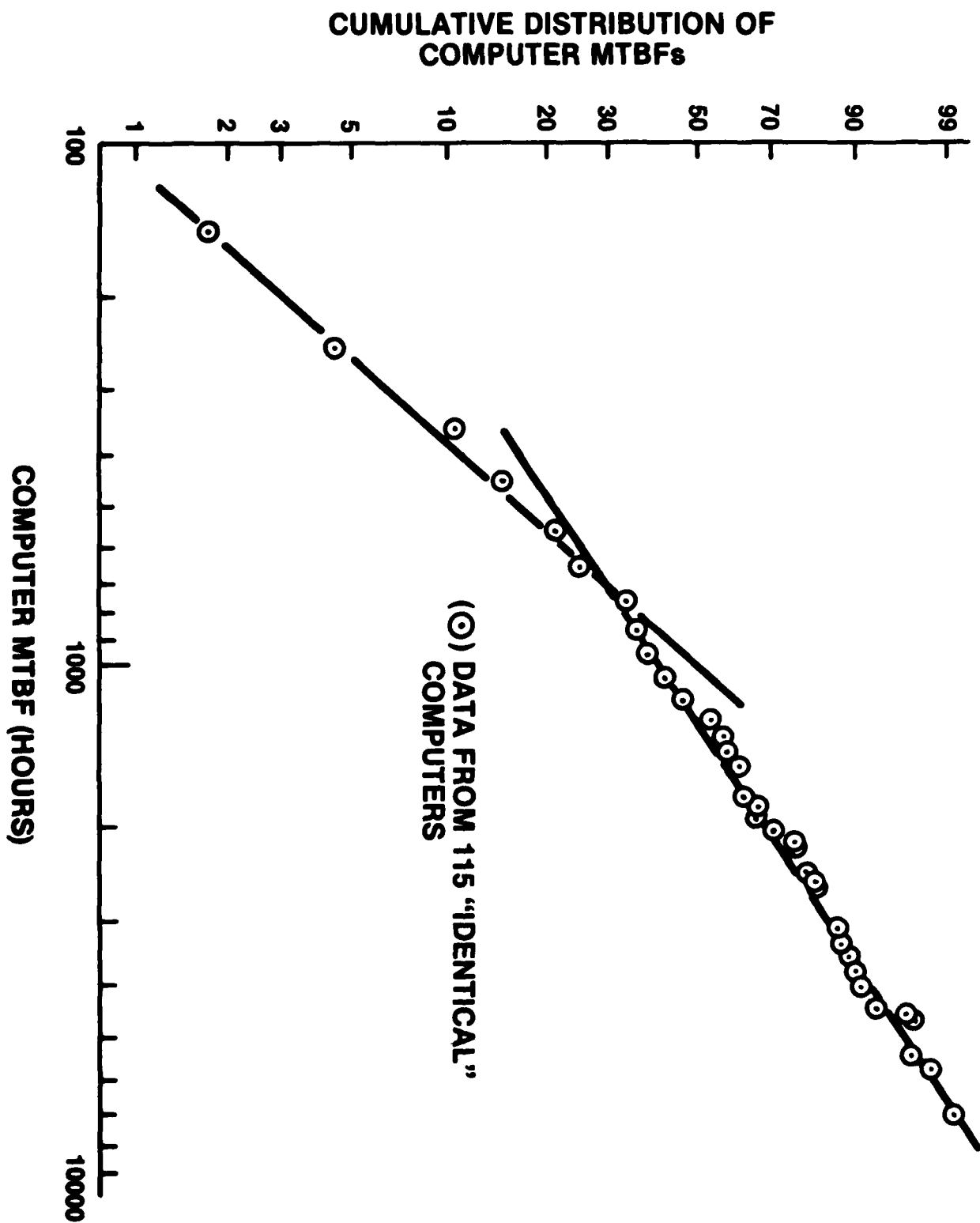


Figure A-2. Weibull Plot of Commercial Computer MTBF Distribution

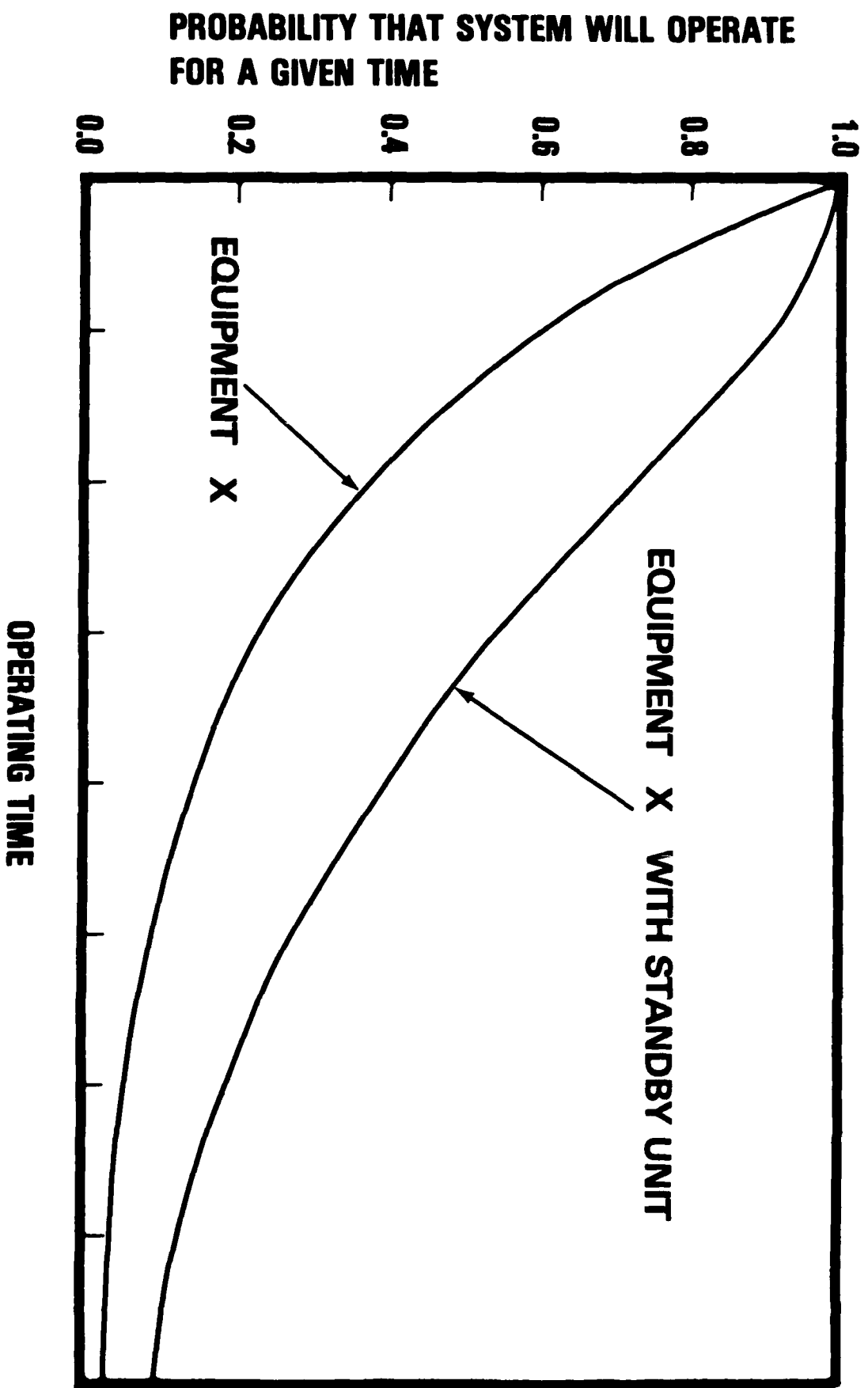


Figure A-1. Reliability of an Equipment with and without a Standby Versus Time

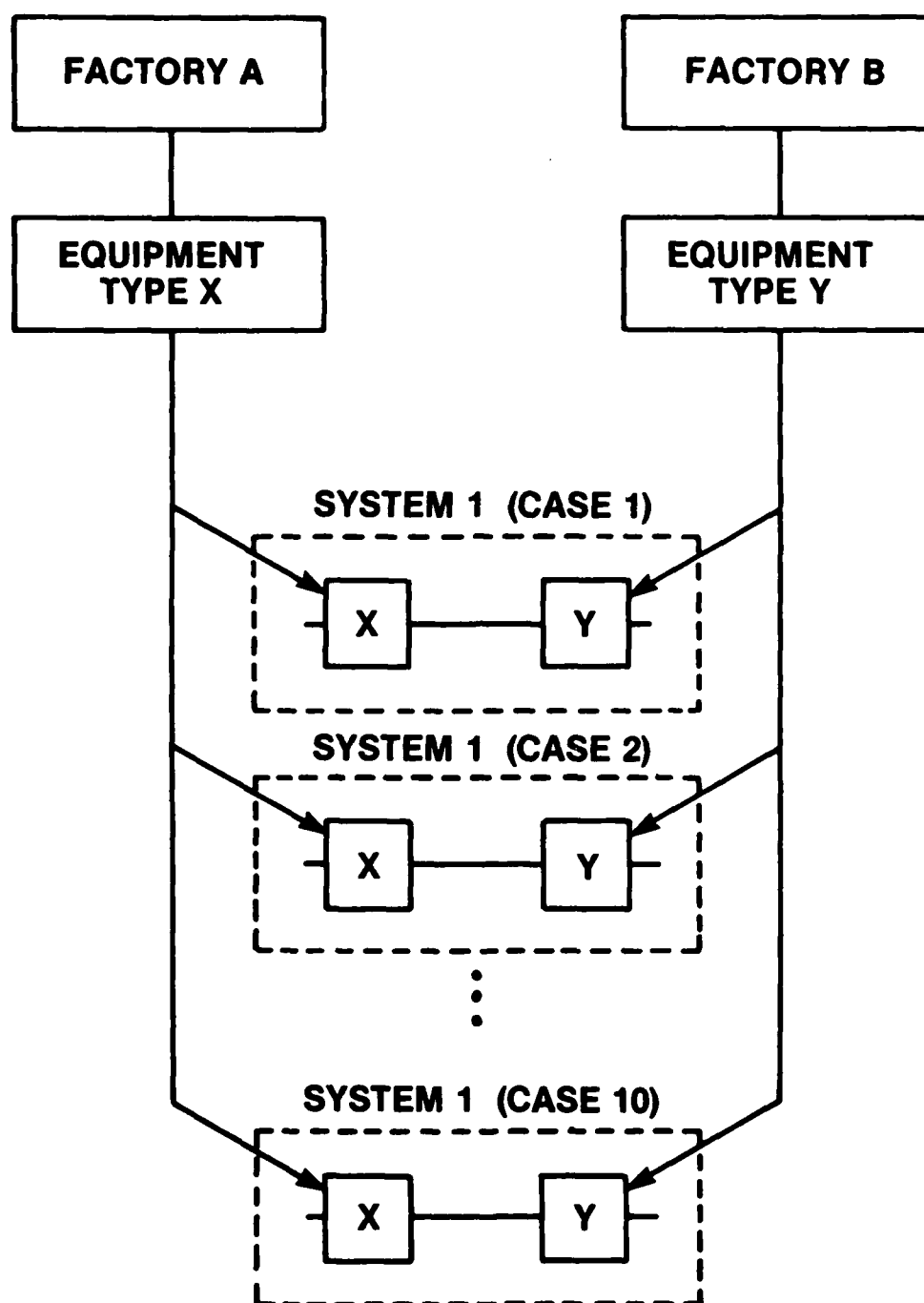


Figure 7. Example Cases Showing how Various MTBFs Can Occur for any Given Equipment.

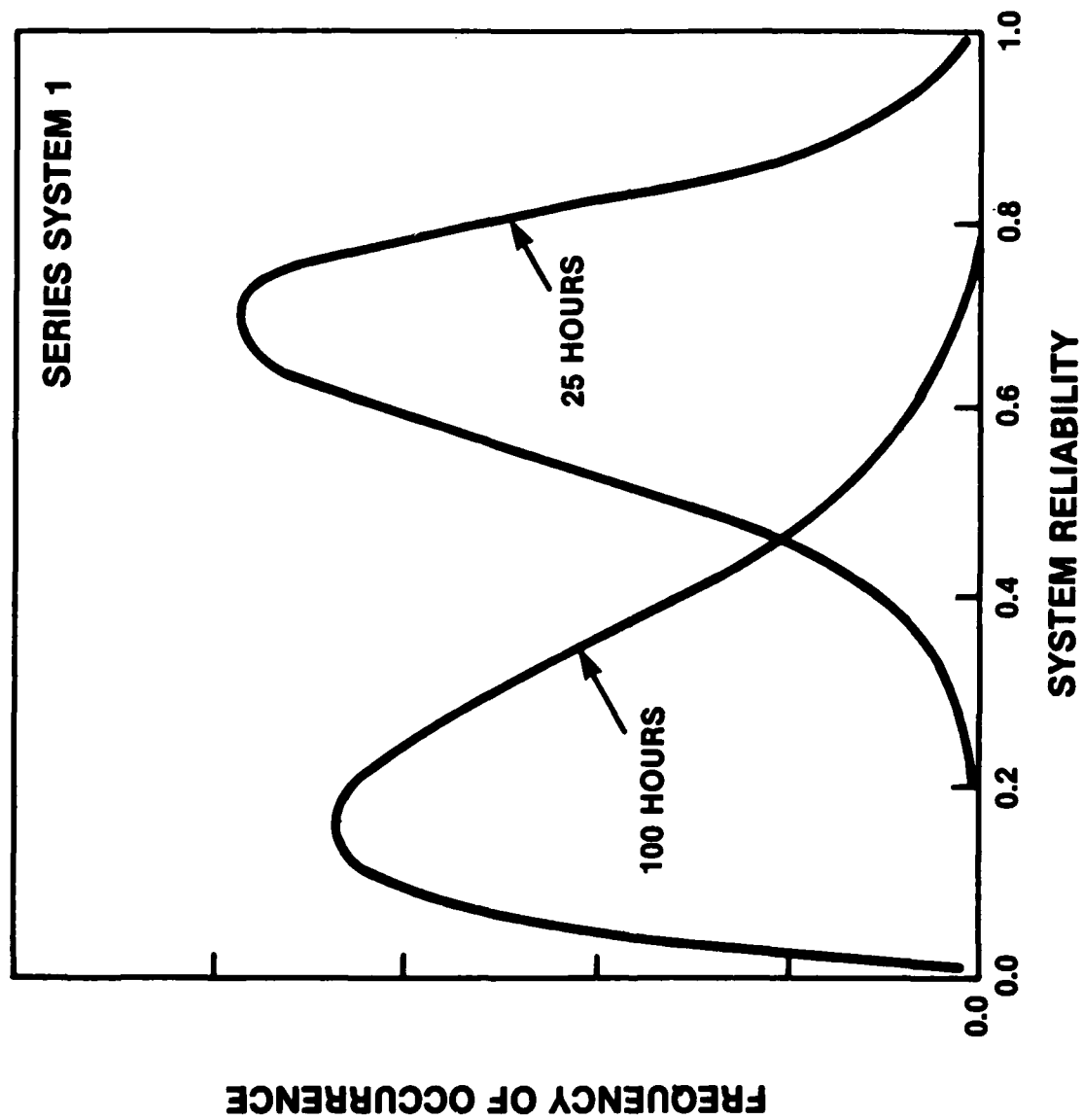


Figure 8. Probability Density Functions (pdf) of the Series System for Two Different Mission Durations

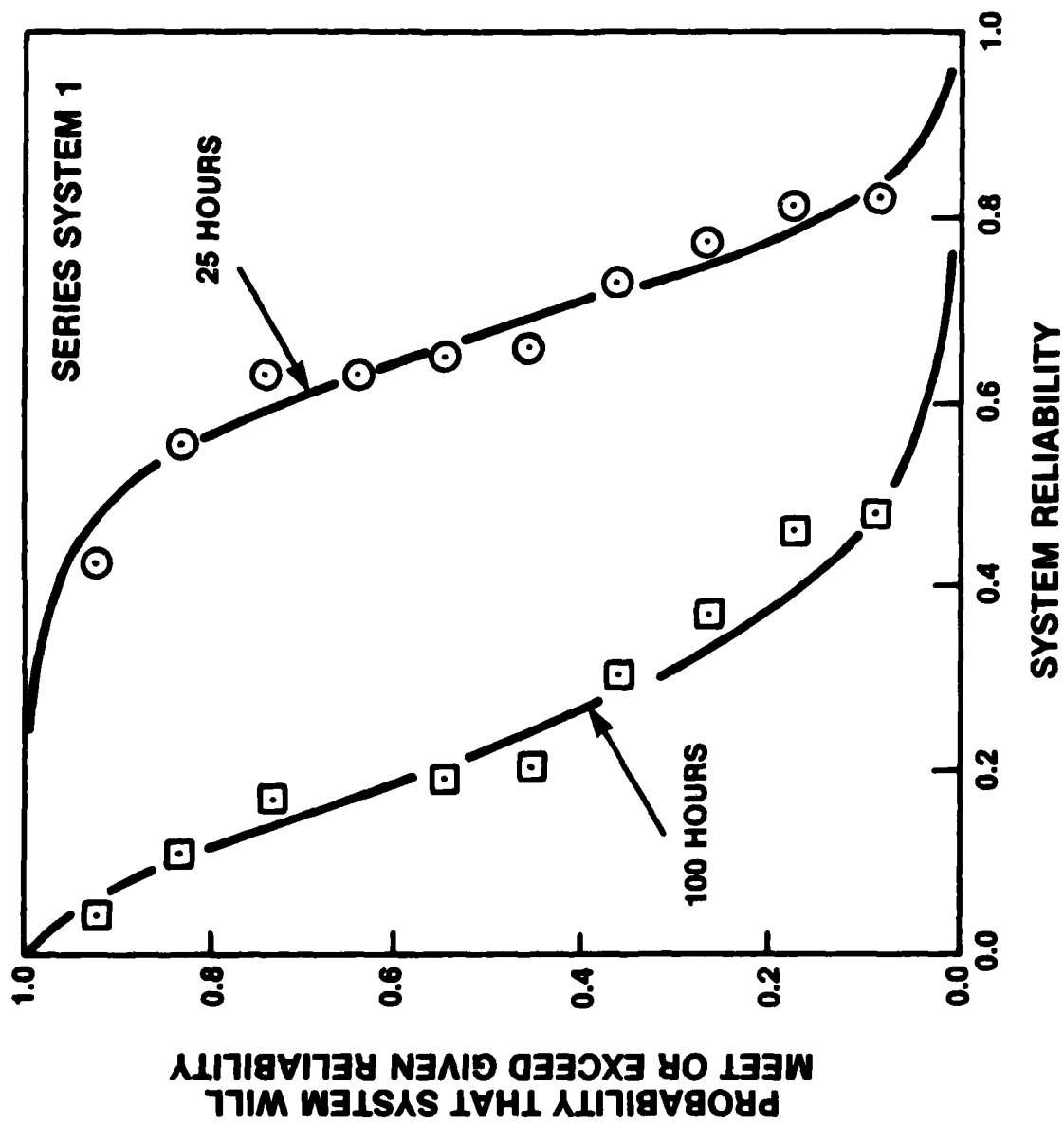


Figure 9. Reliability Performance Data and Cumulative Beta Distribution for the Series System

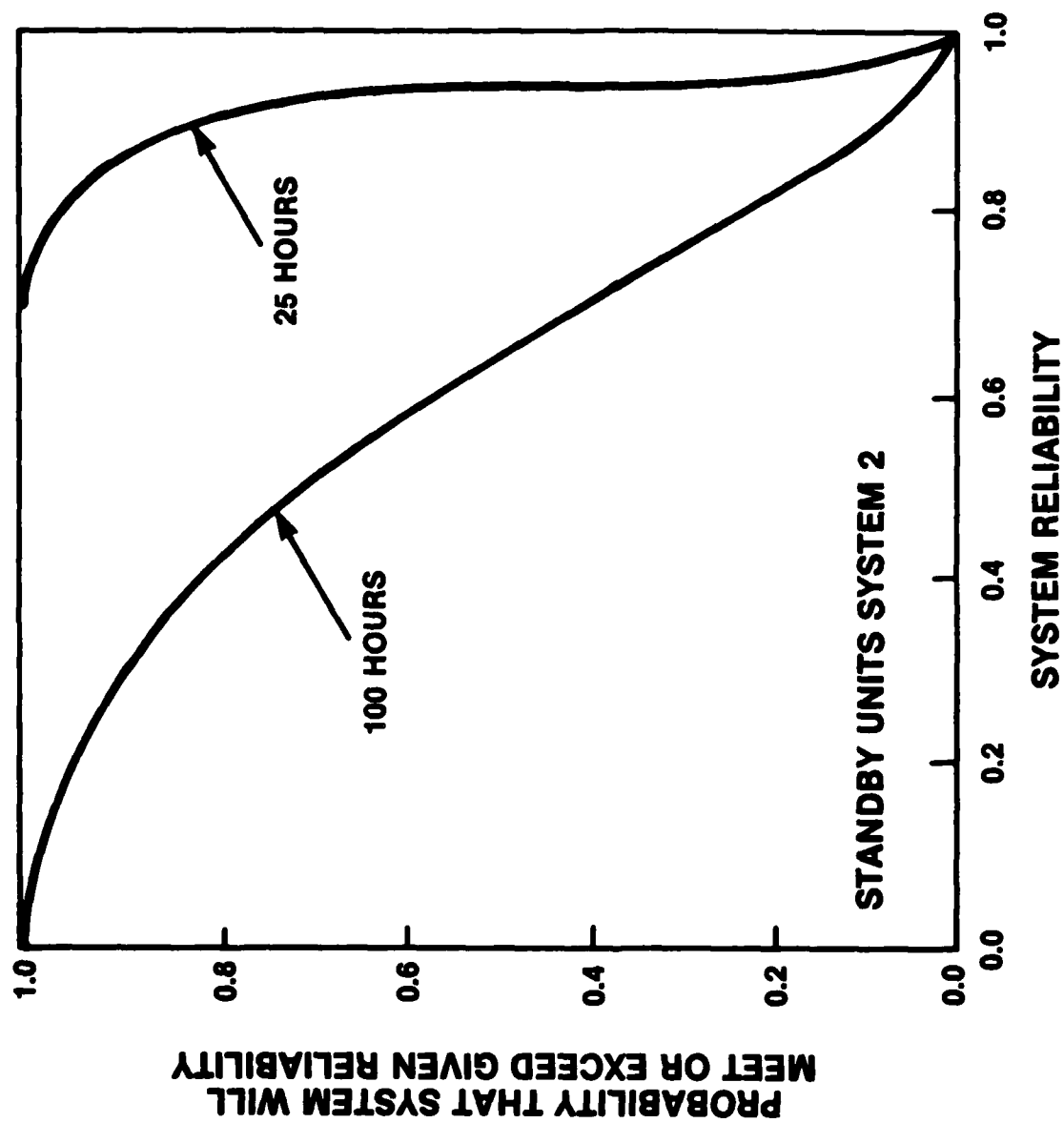


Figure 10. Cumulative Beta Distribution for the Standby System



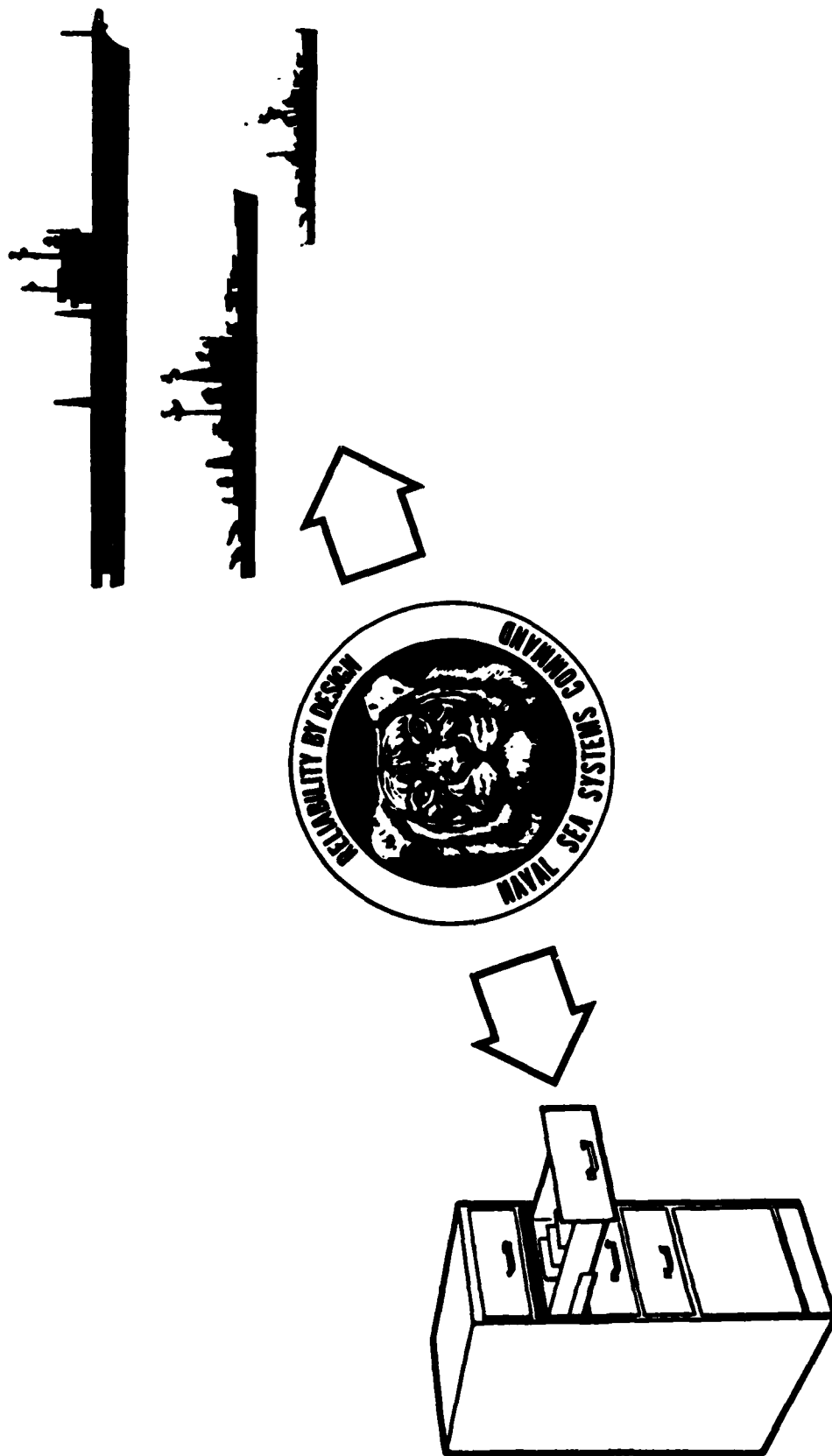


Figure 11. Range of TIGER Applications

Table 1. Varied Reliability Performance for the Example Systems  
Given Gamma Distributed Equipment MTBFs

CASE NUMBER	MTBF <sub>x</sub>	MTBF <sub>y</sub>	SYSTEM RELIABILITY			
			SYSTEM 1 (SERIES)		SYSTEM 2 (SERIES PARALLEL)	
			OPERATING TIME (HOURS) 25	100	OPERATING TIME (HOURS) 25	100
1	64.8	371.0	0.64	0.16	0.94	0.53
2	212.0	325.0	0.82	0.46	0.99	0.88
3	185.5	492.5	0.83	0.48	0.99	0.88
4	46.0	85.0	0.43	0.04	0.86	0.24
5	139.5	113.5	0.67	0.20	0.97	0.65
6	117.5	283.0	0.74	0.30	0.98	0.75
7	295.5	69.0	0.64	0.17	0.95	0.55
8	63.0	144.5	0.57	0.10	0.93	0.45
9	420.0	69.5	0.66	0.19	0.95	0.56
10	162.0	263.0	0.78	0.37	0.99	0.82

END

FILMED



EDITION